AIP | Review of Scientific Instruments

Instrumentation for trace detection of high explosives

D. S. Moore

Citation: Review of Scientific Instruments **75**, 2499 (2004); doi: 10.1063/1.1771493
View online: http://dx.doi.org/10.1063/1.1771493
View Table of Contents: http://scitation.aip.org/content/aip/journal/rsi/75/8?ver=pdfcov
Published by the AIP Publishing

Articles you may be interested in

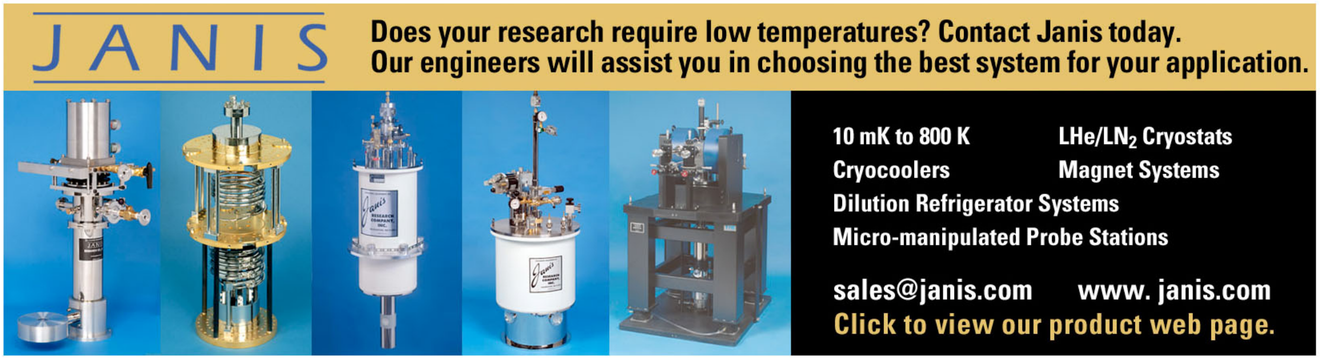
Sensitive trace gas detection with cavity enhanced absorption spectroscopy using a continuous wave external-cavity quantum cascade laser
Appl. Phys. Lett. **103**, 131114 (2013); 10.1063/1.4823545

Selectively coated photonic crystal fiber for highly sensitive fluorescence detection
Appl. Phys. Lett. **90**, 111101 (2007); 10.1063/1.2713132

Selective trace gas detection of complex molecules with a continuous wave optical parametric oscillator using a planar jet expansion
Appl. Phys. Lett. **90**, 081109 (2007); 10.1063/1.2709515

Gamma Resonance Technology for Detection of Explosives, Revisited
AIP Conf. Proc. **680**, 919 (2003); 10.1063/1.1619858

The samarium fullerene family
AIP Conf. Proc. **544**, 159 (2000); 10.1063/1.1342490



JANIS
Does your research require low temperatures? Contact Janis today.
Our engineers will assist you in choosing the best system for your application.

10 mK to 800 K
LHe/LN$_2$ Cryostats
Cryocoolers
Magnet Systems
Dilution Refrigerator Systems
Micro-manipulated Probe Stations

sales@janis.com www. janis.com
Click to view our product web page.

HTML ABSTRACT + LINKS

REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 75, NUMBER 8 AUGUST 2004

REVIEW ARTICLE

Instrumentation for trace detection of high explosives

D. S. Moore
Group DX-2, MS P952, Los Alamos National Laboratory, Los Alamos, New Mexico 87545

(Received 23 December 2003; accepted 26 April 2004; published 26 July 2004)

There is at present an urgent need for trace detection of high explosives, with applications to screening of people, packages, luggage, and vehicles. A great concern, because of recent terrorist activities, is for the development of methods that might allow detection and identification of explosives at a stand off distance. Nearly every analytical chemical method has been or is being applied to this problem. This review outlines the properties of explosives that might be utilized in detection schemes, discusses sampling issues, presents recent method developments with particular attention to detection limits, speed of analysis, and portability, and looks towards future developments. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1771493]

I. INTRODUCTION

In the post September 11, 2001 world, the need to detect explosives, and chemical and biological agents, at extremely trace levels as well as at a stand off distance has been thrust to the forefront in popular media and people's minds. Hardly a day goes by without another suicide attack or car bomb somewhere in the world. The safety of civilized people depends on the capability to detect explosive materials at a distance.

Yet, even before the realities of terrorist actions were felt even on the previously-thought-to-be-impenetrable soil of the US, nearly all, if not all, known instrumental methods had already been investigated for their applicability to the detection of explosive materials.[1–9] The methods can be subdivided into those that detect vapors or particles emitted from the materials, those that detect dissolved or suspended solids in solutions, and those that probe solid materials. Vapor or particle detection systems are best suited for personnel monitoring, such as in portals, but none of the methods investigated to date solves the simultaneous problems of speed, sensitivity, and selectivity required for, e.g., passenger screening. A wide variety of very sensitive methods have been developed for environmental analysis of explosives and/or their degradation products, where the speed requirement is much relaxed. The characteristics of some of those methods allow them to be adapted for use in the detection of illicit or hidden explosives, so they are discussed in this review.

The most difficult area of research and development is for methods appropriate for stand off detection of concealed explosives.[10] So far, mostly nuclear methods have been investigated for this application,[3] but these suffer from lack of societal acceptance. Even recent technologies such as millimeter wave and terahertz imaging will find it difficult to penetrate metal-skinned objects such as trucks and vans.[1]

The United States Bureau of Alcohol, Tobacco, and Firearms lists nearly 250 explosive materials.[11] These materials can be loosely lumped into the following categories (see Glossary for names and abbreviations): military explosives (e.g., TNT, HMX, RDX, PETN) and compositions (e.g., Amatol, Comp A-3, Comp B, Comp C-4, Cyclotol, Detasheet, H-6, HBX-1, LX-10, LX-17, Octol, PBX-9404, PBX-9501, PE 4, Pentolite, Semtex-H, Tritonal); dynamites; ammonium nitrate based explosives; slurry and emulsion explosives; propellants; and special purpose explosives (detonation cord, blasting caps, primers). TNT (2,4,6-trinitrotoluene) is one of the most widely used military explosives and has been in use for about the last 100 years (mostly during World War I (WWI) and II (WWII). DNB (1,3-dinitrobenzene) was produced in large quantities during WWI (second only to TNT), and to a lesser extent during WWII. Picric acid (2,4,6-trinitrophenol) was the third most produced explosive during WWI, but was barely used in WWII. RDX (hexogen) is more recent, was the second most produced explosive during WWII, and is still in very wide use today, especially in plastic bonded explosives (PBX). PETN (pentaerythritol tetranitrate) is also used in PBX. HMX (octogen), related chemically to RDX, is a very powerful military explosive and has been employed in solid-fuel rocket propellants and in military high performance warheads. Military explosives currently used are mostly a combination of TNT, RDX, PETN, HMX, etc. with a number of organic compounds (waxes, plasticizers, stabilizers, oils, etc.). Nitroglycerin (NG) and ammonium nitrate (AN, NH_4NO_3) are used as the basis for other families of explosives (dynamites in the case of NG), typically for industrial applications and in solid rocket propellants. Note that pure AN does not contain carbon; it has been widely used to fabricate bombs, but is also widely utilized as a fertilizer. Ammonium perchlorate (AP) is used as the basis of solid rocket propellants. EGDN (ethylene glycol dinitrate) is a transparent, colorless liquid explosive, which has been used in mixtures with NG for low-temperature dynamites. Its use has greatly decreased due to the replacement of dynamites with ammonium nitrate-fuel oil (ANFO) and slurry explosives. Black powder is a low-order explosive consisting of potas-

© 2004 American Institute of Physics

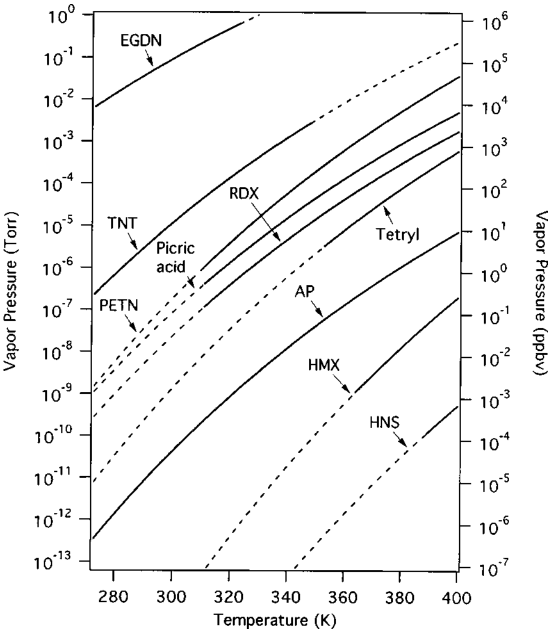


FIG. 1. Plots of the vapor pressure of several common high explosives versus temperature (see Refs. 11–13). Solid curves—approximate measured regions; dashed curves—extrapolations.

sium nitrate (KNO_3) or sodium nitrate ($NaNO_3$), charcoal, and sulfur (it therefore probably does not contain hydrogen). Two materials that have recently become fashionable among terrorists because of their ease of manufacture are triacetone triperoxide (TATP) and diazodinitrophenol (DDNP or Dinol). Both compounds are extremely unstable and easy to initiate. DDNP is used in nonelectric detonators. Otherwise, there is little commercial use of either material.

Explosives are notoriously difficult to detect. There are a variety of reasons, both physical and chemical, for this difficulty. First, the vapor pressure of most common explosives is small; in the case of the highest priority explosives it is vanishingly small.[12–14] The vapor pressure curves versus temperature for some standard explosives are given in Fig. 1 (the dashed curves are extrapolations below and above the regions of thermal stability of many of these materials, which are approximately indicated by the solid curves). Therefore, methods that rely on sampling of air spaces need to either sample very large volumes or have exceedingly small detection limits. Alternatively, particle samplers can be used. A single particle of 5 μm diameter contains as many RDX molecules as 1 L of equilibrium vapor pressure STP air. Second, composite materials such as PBX actually serve to suppress the already small vapor pressures. Third materials are usually packaged by would-be terrorists or others using materials that further block escape of vapors. Kolla[15] estimates that the effective vapor pressure can be reduced by a factor of 1000 by sealing in plastics. Davidson *et al.*[16] state that only the highest vapor pressure explosives can be detected under real world conditions because of the attenuation of vapors by packaging. While such packaging is intended to make explosives extremely difficult to detect via their vapors, there is a chance that the perpetrators would leave fingerprints on the outside of the package. Fingerprints can contain many μg of material, which can then be detected.[7,18] Fourth, a standard technique of raising the temperature to achieve higher vapor pressure often leads to thermal degradation of the material, complicating or inhibiting detection. Finally, interferences leading to false alarms are a difficulty, either because of the inherent lack of selectivity (i.e., ability to differentiate between substances) or because the technique actually detects an additive or impurity, which could also come from sources other than explosives, such as solvents, plastics, etc. False positives can also be nuisance alarms where trace amounts of the material are detected even though no bulk material is present.

The most important shortcoming of all detection methods developed and implemented to date is the small subset of explosive materials that have been used in their design, characterization, and/or calibration. Nearly all detection methods have been developed and tested against just a few explosive materials, usually TNT, RDX, HMX, TATB, PETN, NG, ANFQ, and perhaps a few other common materials, impurities, or decomposition products. While this shortcoming is not critical for research and development, implementation would seem to be more appropriately preceded by characterization using a larger spectrum of materials. The lack of standard reference materials containing more than the usual explosive components contributes to this shortcoming. Accustandards[19] has several reference material solutions available (at 0.1 and 1 mg/mL concentrations), as does Absolute Standards, Inc.,[20] but these only contain a variety of amino nitrotoluenes and nitrobenzenes plus RDX, HMX, and tetryl (up to 14 components), as defined by EPA Method 8330 (Ref. 21, see HPLC section below). Still, the availability of any reference materials or solutions is a great improvement that has occurred in just the past few years and will help future method development and qualification efforts.

Another shortcoming is the lack of comparison of methods on the same basis, including sampling and preconcentration (which is a sample collection method wherein the analyte concentration is increased). There is a need for standard reference materials in this case as well, or at least a standard method to generate vapors or particulates at known concentrations and with known concentrations of common interferents.

There have been several recent reviews and other papers on instrumentation designed for environmental contamination analysis and also on instrumentation for detection of bulk explosives in containers, especially for luggage and vehicle screening applications.[22–31] This review will concentrate instead on instrumentation designed to detect, identify, and quantify trace explosive vapor or particles. The review will be divided into sections each devoted to a particular method. Within each section the methodology will be briefly described using seminal and recent references, and detection limits and interferences will be discussed.

All the methods discussed in this review can be schematically represented as in Fig. 2. The general scheme includes some kind of sampling methodology (which may or may not also preconcentrate the analyte), an optional separation step (which may occur during sampling and/or preconcentration), an optional orthogonal detection method (commonly referred to as hyphenation), and finally the detection

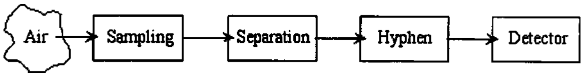


FIG. 2. Schematic representation of a general trace explosive detection method. Sampling or preconcentration can be followed by a separation step, an optional orthogonal analytical method (so-called hyphenation), then the detection method. Often the sampling or preconcentration provides the separation.

method. For example, GC-ECD (see below) includes a sampling step (usually SPE or SPME), GC as the separation step, and ECD as the selective detector. Because all the discussed methods can be similarly represented, detailed schematics of each are not included. Interested readers can consult the relevant references for details.

II. PROPERTIES OF EXPLOSIVES

The unique properties of high explosives originate from the presence, in the same molecule, of fuel and oxidizer.[12–14] This proximity leads to the ability to achieve extremely high reaction rates because diffusion is not the rate-limiting step. Nitrogen is present in nearly all high explosive compounds, and usually acts as the inert substance separating fuel from oxidizer. This is not always the case, as strained ring or other structures with high enthalpy of formation ΔH_{f} can also react explosively, with ambient stability provided by large activation energies. As most explosives contain carbon, hydrogen, nitrogen, and oxygen, they have been categorized via their CHNO elemental ratios. Most common explosives are rich in nitrogen and oxygen and poor in carbon and hydrogen. One indicator for explosives is the oxygen/nitrogen ratio. Many bulk detection methods rely on anomalously large nitrogen content. Trace detection methods rely instead on a molecular signature of some kind, such as a retention time (chromatography), a vibrational spectrum, a mass spectrum, or a specific interaction with a surface or molecular lock and key.

Explosives have a variety of vapor pressures (see Fig. 1) at room temperature, from high (torr level from EGDN), through microtorr, as from TNT or DNT, to sub-nanotorr, as from HMX, making their detection via vapor methods potentially extremely difficult and material dependent. Most vapor detection methods have been demonstrated for materials with relatively high vapor pressures, such as TNT and DNT, or with heating, where decomposition is usually problematic. Therefore, collection and detection of high explosive particulates is particularly attractive. These particles can adhere to surfaces or can be airborne. They can be collected as discussed in the next section on sampling. For testing of instrumentation under development, a number of vapor generators and solid particle generators have appeared. This topic is discussed further below.

III. SAMPLING AND PRECONCENTRATION

Because vapor pressures are very low for most explosive materials, vapors are usually preconcentrated in some manner to improve ultimate volume detection limits.[32–56] Explosives have been found to adhere to a variety of materials such as Teflon, glass, quartz, nickel, stainless steel, gold, platinum, copper, fused silica, aluminum, and plastic. A typical preconcentration scenario is to flow a specific volume through a fine mesh, membrane, ribbon, or long tube of the material at room temperature, followed by flash heating to a higher temperature (ca. 150 °C) and injection of the smaller trapped volume into the analytical detection system.[32–34] Several coating materials with larger trapping efficiencies [such as solid phase extraction (SPE) or gas chromatographic polymers, and even fullerenes] have been tested to decrease the collection time needed for a given detection limit.[57–60]

There have also been efforts to develop species selective coatings for preconcentrators, so that a separation step is included in the sample collection (see, e.g., Ref. 58). These have been coupled to a surface acoustic wave (SAW) device (see Ref. 105 in See. VII A) for direct detection of specific species.

The adsorption efficiency can be affected by ambient temperature, so that detection limits based on collection of the prescribed volume of air at the prescribed flow rate may be out of calibration at different environmental conditions.[52–56] The preconcentration step increases the time required for the measurement, sometimes to times longer than suitable for on-line use. To improve the selectivity of species-selective coatings for preconcentrators, future polymer developments that enable an increasing percentage of multiple polymer interactions with each nitro functional group of the polynitroaromatics holds the promise of an increase in polymer-nitroaromatic air partition coefficients and hence sensor signals. In addition, as the polymer interaction with increasing numbers of target molecule functional groups increases, the selectivity of the polymer coated sensors relative to other background vapors will be substantially increased.[57–60] Houser *et al.* have demonstrated detection of <100 parts per trillion by volume (pptv) for DNT, with evidence of interference from water vapor using such polymers.[58]

The other concept on sampling is to collect particles by vacuuming or otherwise sweeping a volume, because the particles either have already done the task of preconcentration or are explosive particles themselves, leading to much easier detection.[61–70] The task of collecting particulates is often performed using portals. Surfaces of potentially contaminated objects can be swiped and the swipe analyzed in a separate step.[21] Sometimes portals also double as swiping devices, such as the designs of Wendel[65] and McGann *et al.*[37]

Because invasive interrogation methods such as x rays or nuclear methods cannot necessarily be used to screen people, a variety of other less invasive methods have been incorporated into portal devices. The most commonly encountered portal is the ubiquitous walk-through metal detector. Recent efforts have been aimed at increasing the efficiency of metal detection portals and incorporating other detection capabilities for explosives or other illicit substances. Technologies fall into two basic categories: imaging and trace detection.[61] Advanced imaging systems include raster scan backscattered x-ray tomography, millimeter wave holography, and microwave detection of dielectric function anomalies.[61–63] Trace detection methods have required incorporating a variety of sampling paradigms in portals to enable collection of vapors and/or particles from subjects. These have included puffers or air jets, paddles, acoustic energy, and other types of airflow. The collected material is then analyzed using ion mobility spectroscopy (IMS), mass spectroscopy with electron capture detection (MS/ECD), and chemiluminescence methods, among others.[32–34,61–70]

Many materials have unique dielectric constants and dissipation factors. For example, air has a dielectric constant near 1 and a dissipation factor near zero and will not absorb microwave energy. The effect has been incorporated in a portal design, which has a sensor with an antenna lens combination that establishes a fixed microwave energy field at 5.5 GHz. Objects that enter the field alter it. The microwave energy penetrates nonmetallic objects and produces a volumetric reflection coefficient, which allows calculation of the dielectric constant and dissipation factor. The portal is able to detect concealed devices and say whether they are metal or something like plastic, but not the chemical composition.[62,63]

IV. CALIBRATION AND TESTING PROTOCOLS

There are very few method calibration protocols or reference materials for vapor sampling, similar to what is available for environmental sampling (EPA Method 8330[21]) or bulk detection (FAA protocols).[23] A test protocol for trace detectors has been presented and tested using a commercial IMS device.[71] There are also a couple of references to what should be done.[16,72] Therefore, there is an urgent need for standard testing protocols to enable fair and complete comparisons of available trace and stand off detection methods.

V. VAPOR AND PARTICLE GENERATORS

In order to calibrate the various detection methods in lieu of certified or reference standards, means to generate known concentrations of explosive vapors[73–83] and well-characterized solid particles[84–86] have been used. This has been accomplished in various manners, including continuous thermal sources, transient methods using gas chromatography (GC) columns and injectors, and pulsed methods, usually using a preconcentrator or precise mass of EM in a known volume. Still, in order to compare methods on equal footing, it would be more desirable to have some sort of standards available, or to arrange an interlaboratory comparison or proficiency test using the same material or samples.

VI. TRAINED ANIMALS

Any review of instrumental trace explosive vapor detection methods would be remiss without inclusion of and comparison to trained animals.[87–97] The canine nose is an extremely sensitive molecular sniffer, able to detect vapors at concentrations three to five orders of magnitude lower than those discernable by people. Dogs are also trainable to perform a specific action when a given material is detected. They are usually trained on specific explosive molecules rather than products so that exact formulations are unimportant. However, often, the particular molecule or mixture the dog actually detects is unknown, and could be an impurity or residual solvent rather than the explosive itself.[95] Several recent studies have provided more information on odor signatures.[95–97] No quantification results have been found in the literature. Trained animals are used as alarms rather than for quantification.

There are problems with use of trained dogs as detectors. They fatigue, their capabilities decline with time, and they suffer from changeable moods and show behavior variations. These difficulties have been extensively discussed in the literature.[87–93]

Other animals, such as rats, have also been studied, but the training and reliability are questionable for dependable detection.[89]

VII. SEPARATIONS METHODS

A. Gas chromatography (GC)

Chromatographic methods are used to separate components in a sample. A sample is pushed through a column by a carrier gas (which constitutes the mobile phase). The various materials in the sample, by virtue of different interactions of each component with the stationary phase in the column, move through the column at different speeds, so that they emerge at different “retention times” and are separated. The separated materials are detected by a device that responds with an intensity that is proportional to the concentration of the component in the mixture. Many different kinds of detectors are used for explosive materials,[98–119] such as electron capture detectors (ECD),[103] chemiluminescence (or thermal energy analyzer—TEA) detectors specific to nitrogen containing species,[98,116] mass spectroscopic (e.g., Ref. 102) (discussed below in Sec. VIII A and surface acoustic wave (SAW) detectors (also discussed below in Sec. XIII).[105]

Rounbehler *et al.* detected NG, EGDN, DNT, TNT, PETN, and RDX in a mixture at the sub-picomolar level using GC-TEA.[116] The detection limits using ECD detection, as reported by Walsh,[103] were 1 mg kg^{-1} for di- and tri-nitroaromatics, 10 mg kg^{-1} for mono-nitroaromatics, 3 mg kg^{-1} for RDX, 25 mg kg^{-1} for HMX, and between 10 and 40 mg kg^{-1} for nitrate esters (nitroglycerine [NG] and pentaerythritol tetranitrate [PETN]). Staples *et al.* achieved pg range detection of TNT and RDX using GC with a SAW detector.[105]

A complete GC-based method for vapor phase explosives has been recently described by Batlle *et al.*, and involves solid phase microextraction (SPME) cartridge sampling and preconcentration, supercritical fluid extraction (SFE), and large volume injection GC separation with nitrogen/phosphorus (TEA) detection.[98] The authors achieved 6–36 pg/L detection limits with a 10 L sampled headspace volume above military grade TNT. The production of a portable, near-real-time device based on this technology would be useful.

B. High performance liquid chromatography (HPLC)

The direct chromatographic separation of liquid samples can be accomplished using high performance liquid chromatographic (HPLC) techniques. The separated components have been detected by a variety of means. In fact, the EPA standard method for trace explosive residue detection in environmental samples is EPA Method 8330, which utilizes

HPLC separation and UV detection.[21] In this method, dilute aqueous samples are preconcentrated using a salting out procedure into acetonitrile, and then injected onto the HPLC column. Soil samples are extracted directly into acetonitrile.

There have been a number of improvements and extensions of HPLC methods, mostly to reduce sample preparation and produce a method that is faster (nearer to real-time) and field portable.[120–125] These improvements have mostly centered on utilizing SPME devices and improving the sample injection interface. Recently, Swedish researchers have developed a method to determine explosives in the vapor phase using on-line coupling of supercritical fluid extraction with high-performance liquid chromatography, achieving 10–50 ng detection limits for military grade TNT.[123]

The recent use of peroxide based explosives by terrorists, due to their ease of manufacture, spurred the development of HPLC based detection methods, with near μM detection limits for TATP and HMTD using fluorescence detection of photochemical degradation products.[120]

C. Capillary electrophoresis (CE)

Separation of ionic species is achieved by the difference in mobility through a fluid driven by a potential difference. Detection is usually accomplished using a change in conductivity. McCord *et al.* demonstrated the separation and detection of components in a mixture of environmental decomposition products.[126] Wang *et al.* have demonstrated several chip-based CE-conductivity microsystems for the rapid separation and detection of ions related to ammonium nitrate based explosives and other EM,[127] separating eight ions associated with ammonium nitrate based explosive post blast residues. Such new microfluidic devices offer significant advantages in term of speed, cost, and sample size.[128,129] For example, Wang *et al.* have recently demonstrated a single channel microchip for fast screening and identification of nitroaromatic explosives.[128]

VIII. ION DETECTION METHODS

A. Mass spectrometry

Mass spectroscopic techniques have received perhaps the most extensive study for the detection of explosives.[130–182] A mass spectrometer separates materials according to the mass to charge ratio of the parent ion and its fragments.[138] A sample is introduced into a high vacuum chamber by various means, where it is ionized using a variety of methods, such as ion impact, electron impact, VUV, and resonance enhanced multiphoton ionization (REMPI). The resultant ions are then accelerated into the spectrometer, which separates them based on geometric path (as in magnetic sector, quadrupole, or ion trap instruments) or time of flight. Conventional type instruments that have been used specifically to detect explosives are an atmospheric pressure ionization (API) tandem mass spectrometer, an atmospheric sampling glow discharge ion trap mass spectrometer (ASGDI—which achieved <pg detection of RDX),[151,152] and an API TOF mass spectrometer (Lee *et al.* reported a 10 fg detection limit for TNT).[182] Several instruments have been developed that take advantage of the large electron attachment cross sections of many explosives. These include a reversal electron attachment mass spectrometer (READ; <100 pg detection limit for TNT)[163–165] and an electron-capture negative ion mass spectrometer (ECNIMS; 20 pg detection limit for PETN).[156–158] This latter instrument allows differentiation between various explosives containing NO_2 fragment ions and between explosives and other nitrocompounds, by observing the electron energy at which the NO_2 ion is formed. Materials containing $C-NO_2$, $O-NO_2$, and $N-NO_2$ bonds can be easily differentiated. A CONDOR APCI tandem MS system was able to detect RDX, PETN, and TNT down to the sub-pg level.[149,160] An ion trap MS (ITMS) was used to detect TNT at the 10 fg level.[180] Denitration reactions in an ion trap MS show promise for sensitive detection of nitroaromatics.[131] The combination of a dual El/Cl ion source with a quadrupole ITMS has recently shown promise for nitro group containing materials.[130]

Hankin *et al.* have recently shown the capabilities of femtosecond laser ionization TOF MS for detection and identification of nitroaromatic compounds. The capability of femtosecond laser ionization to generate consistent and reproducible precursor and high-mass fragment ions is valuable for complex molecular identification and quantification.[132]

B. Ion mobility spectrometry

The technique that has been applied most ubiquitously for detection of explosives vapors and particles, mostly because of the availability of portable instruments, is ion mobility spectrometry (IMS).[183–212] An ion mobility spectrometer consists of a sample inlet system, an atmospheric pressure ion source, an ion-molecule reactor, an ion-drift spectrometer, and a detector. Sample ions formed in the reactor are swept into the drift region by an applied electric field. They are separated according to their mobility as they travel through the drift gas; their mobility depends on their mass/charge ratio. Usually, mobilities are ratioed because the ratio is independent of operating conditions and permits use of internal standards for calibration. The long history of the use of IMS to detect explosives coupled with strong understanding of the species produced in the ionization process for typical explosives make IMS widely utilized in the field (see the reviews in Refs. 183–186 and also Refs. 1–9).

A newer variant known as transverse field compensation IMS (Ref. 212) eliminates the gating electrodes needed to pulse ions in conventional IMS so that ions are continuously injected. Instead two oscillating electric fields are applied in the drift region. Sweeping the second (compensating) field through a voltage range produces the spectrum.

Several other new advances have been recently made. Ionization region reactions have been optimized for TNT, PETN, and RDX using a negative corona discharge.[187] Wu *et al.* have adapted an IMS to portal sampling by adding a high flow collector and improving the IMS resolution.[188] A huge increase in sensitivity was achieved by development of a micro-Faraday array detector.[189] Finally, IMS has been optimized for sensitive and selective detection of the recent terrorist-favorite peroxide explosive TATP.[190]

The major problem with IMS is that it is difficult to quantify. Therefore, it is usually used as an alarm for presence of a species, rather than for quantification. In addition, IMS suffers from masking by other species in the environment or false alarms by nonexplosive species, so that it needs an additional orthogonal analytical method to reduce false alarm rate as well as to provide quantification. Hill and Simpson[185] said "It is still difficult to find good quantitative data…for IMS." One hyphenated method involving separation using GC and detection by IMS achieved 5 pg detection limit for TNT with enhanced selectivity.[211]

A very similar technique to IMS is described by a Russian group as ion drift nonlinearity spectroscopy.[213,214] Any significant instrumental differences do not seem to yield superior results. The terminology difference may be a consequence of Russian authors.

IX. VIBRATIONAL SPECTROMETRIC METHODS

A. Infrared absorption spectroscopy

Molecular vibrations have characteristic frequencies in the infrared spectral range (tens of cm^{-1} to several thousand cm^{-1}). Resonant absorption of light by these vibrations can be observed when light of the appropriate frequency is present, and when there is a change in the molecular dipole moment for that particular molecular vibration. IR absorption methods have been studied extensively for application to the detection of explosives;[215–236] the literature to 1998 was reviewed by Steinfeld and Wormhoudt.[6] Vibrations involving the NO_2 moiety have strong infrared absorption signatures, and their vibrational frequencies depend characteristically on the molecule, so that they can be used as a fingerprint. Infrared spectra of large molecules in the vapor phase can be quite complicated and have large bandwidths, which lead to indistinct spectra. Also, a large number of explosives decompose at the elevated temperatures needed to achieve high enough vapor pressures to allow detection, so that the spectra are further complicated by the decomposition products (but see the next section for a use for this idea[237–245]). Typical absorption cross sections (peak values, not band integrated) for NO_2 stretching modes in explosives are in the range $1-10\times 10^5\ \mathrm{cm}^2/\mathrm{mol}$.[216,232–236] Therefore a cell with 100 cm path length allows detection of 10 ppm (by volume) of vapor (TNT at 60 °C), which is quite inadequate.[216]

Recently solid phase microextraction (SPME) methods have been coupled with IR absorption spectroscopy of the SPME films to determine nitroaromatics in water.[59] The SPME polymer film has no absorption bands in the NO_2 stretch region to interfere with the analyte peaks. The authors achieved a detection limit of 50 μg/L for TNT.

Finally, selective absorption coatings on SAW devices have been coupled to FTIR via attenuated total reflection (ATR) methods. Selective coatings for DNT and TNT have recently been achieved via self assembly of cyclodextrin monolayers.[215]

B. IR detection of decomposition products

The predisposition of energetic materials to decompose on heating has led several groups of researchers to utilize the effect for detection.[237–245] A number of groups have concentrated on driving the decomposition process using catalysts and detecting the stable molecular fragments using frequency modulation spectroscopy with diode lasers.[237–241] Riris *et al.* have achieved a 5–10 pg detection limit for RDX using these techniques.[238] Thermal decomposition and detection of fragments are also the means for operation of the Thermedics Detection EGIS system in use at many airports.[116,242,243] The fragments have also been detected using Stark-modulated millimeter wave spectroscopy.[244] Alternatively, fragmentation can be induced via laser decomposition techniques. Coupling laser decomposition to multi-photon ionization methods can result in excellent detection limits (i.e., 3 pg for TNT and 1 pg for RDX).[245]

C. Cavity ring down spectroscopy

In order to increase the effective path length for infrared and UV/visible absorption methods, cavity ring down spectroscopy (CRDS) has been applied.[246,247] The principle of CRDS is as follows. Light from a pulsed or CW laser source is injected into a stable optical cavity formed by two, or more, highly reflective mirrors. At the end of the laser pulse (or, in the case of a CW laser, after the laser is turned off) the intracavity radiation will decay exponentially with a time constant that is determined by the reflectivity of the mirrors, the scattering inside the cavity (such as Rayleigh scattering of the gas sample), and the wavelength dependent absorption of the intracavity gas. Measurement of the ring down time versus wavelength of the injection laser produces the equivalent of an absorption spectrum. The noise floor of a good cavity ring down instrument in the mid-infrared is ca. $A=1\times 10^{-8}$ (Ref. 246). The NO_2 stretch band peak absorption cross section of ca. $10^6\ \mathrm{cm}^3/\mathrm{mol}$ implies TNT would be detectable in the vapor at room temperature, but other materials would need some kind of preconcentrator. CRDS has also been performed using UV transitions of TNT in the vapor phase.[247] The spectral selectivity for differentiation from other species is poor. Nevertheless, the authors report a detection limit of 1 ppb (by volume) for TNT.

D. Optoacoustic spectroscopy

Optical energy absorbed by molecules is partially turned into thermal energy via nonradiative relaxation processes. This thermal energy can be detected via the rise in temperature and pressure in a cell containing the molecules of interest. If pulsed or chopped radiation is used for excitation, the pressure pulses can be detected using a sensitive microphone or piezoelectric transducer located within the cell. A photoacoustic absorption spectrum can be obtained by phase sensitively recording the normalized transducer signal versus wavelength of the excitation source.[248,249] These techniques have been applied to detection and identification of explosives, using infrared laser sources and obtaining vibrational spectra for the reasons discussed above (narrow transitions, large absorption cross sections, and species specific spectral features).[250] Good detection limits were obtained (NG: 0.28 ppb; EGDN: 8.3 ppb; DNT: 0.5 ppb), but ambient levels of CO_2, H_2O, NH_3, and O_3 interfere strongly at the

9.6 μm excitation wavelength.[250] A variant of this method, laser interferometric calorimetry, has also been applied to detection of explosives with detection limits in the ppt (trillion, by volume) range for TNT.[251,252]

E. Raman scattering

The complementary vibrational spectroscopic technique to infrared absorption, Raman scattering occurs because of the inelastic scattering of light from molecules or atoms.[253] During the interaction of the primary light quantum with a molecule or crystal, the energy of vibrational and/or rotational states may be exchanged and a secondary light quantum of lower or higher energy is emitted. The energy difference is equal to the vibrational energy E_{vib} of a molecule or crystal and/or the rotational energy E_{rot} of a molecule. It may be recorded, if monochromatic radiation is used for the primary excitation, as a vibrational, rotational, or rotation vibration Raman spectrum. The inelastic interaction of a primary light quantum with a molecule or crystal in its rotational or vibrational ground state produces the Stokes Raman spectrum, a redshifted spectrum.[253,254]

Recent Raman spectrometers for detection of explosives have been of the dispersive type with charged coupled device (CCD) detection and of the Fourier-transform type with excitation at 1064 nm and a near infrared detector.[254–270] The use of the reddest excitation possible minimizes complications due to sample fluorescence. However, sample heating can be a problem because the $1/\lambda^4$ scattering cross section dependence on wavelength tends to require larger excitation energies at these longer wavelengths. The dispersive/CCD type Raman instruments have been made quite portable (<10 kg total weight) facilitating field use. Fluorescence interferences and the extremely weak nature of the Raman effect make the use of Raman for trace detection of explosives problematic unless resonance or surface enhancement methods are used.[6]

Raman has been used successfully to detect residual explosives in fingerprint samples,[261,262] among other small sample detection schemes.[263–270] While Raman has the capability to detect very small solid samples of pure material (i.e., $<1\ \mu\mathrm{m}^3$ particles[263]), detection limits are too large for Raman to be used for vapor phase detection at very low levels. However, Raman signals can be enhanced using UV wavelength excitation via both the $1/\lambda^4$ wavelength dependence and resonance enhancement as electronic transitions in the target molecules are approached.[254] Wu *et al.* have utilized UV resonance enhancement in a mini-Raman LIDAR (light detection and ranging) apparatus for stand off detection of explosives.[271,272] Their device has been applied to solid and liquid targets, but not vapors, to date.

F. Surface enhanced Raman scattering

Another method that can be used to dramatically increase Raman scattering signals is surface enhancement.[273,274] Noble metal nanostructures or nanoparticles can cause large enhancements (up to $\times 10^6$) of the Raman scattering cross section for adsorbed molecules. The origins of this effect have been in dispute, but recent advances in production of nanostructures with very precise control of their size, shape, and spacing have allowed both greater understanding of the origin of the effect and its control.[275] Small metal nanoparticles or nanostructures have a localized surface plasmon resonance that appears to provide most of the Raman enhancement, maximized when the localized surface plasmon resonance (LSPR) frequency overlaps that of the excitation laser. There also appears to be a small "chemical" contribution to the enhancement caused by changes in the bond polarizability of an adsorbed molecule.

Early SERS experiments were not very reproducible due to variations in the roughness of surfaces, or to variable production of colloids or other small particles. Recently, several different schemes have been developed to produce highly uniform and reproducible LSPR nanostructures from several different materials.[275–281] Silver nanostructures are most common and provide to date the largest enhancements, but suffer from oxidation and other chemical attack. Gold nanostructures have the advantage of a large enhancement and chemical robustness. The production schemes include vapor deposition through self-assembled monolayer masks,[275] electrochemical etching protocols,[276–278] templated self assembly of colloidal crystals,[279,280] and annealing of vapor plated metal islands.[281]

SERS on colloidal Au nanoparticles was used to detect TNT at $<1<$pg (<100 pM) levels.[279] Using principal component analysis (PCA) of SERS spectra of explosives isolated on OH treated electrochemically etched silver, Sylvia *et al.* achieved a detection limit for TNT and DNT of <5 ppb (volume).[277] SERS has also been used to detect selectively functionalized TNT, which provides an additional enhancement due to the resonance Raman effect, with detection limit much better than 1 nM in solution.[282]

There are now commercial SERS materials available, particularly for aqueous samples and other environmental samples.[283] However, there still exists a need for commercial robust and reproducible SERS substrates for vapor analysis. The number of groups involved in SERS efforts for chemical/biological weapon (CBW) and explosives detection has increased dramatically in the past few years, as demonstrated by the large number of relevant symposia at analytical instrumentation conferences in 2003 (FACSS—www.facss.org—and Pittcon—www.pittcon.org).

X. UV/VISIBLE METHODS

UV/visible absorption spectra of typical explosives are broad and featureless, making their use for qualitative analysis difficult or impossible.[284–288] However, the absorptions can provide resonance enhancement for other methods, such as Raman (UVRRS).[271,272,289] There are very weak absorptions in the visible that are accessible via photoacoustic methods,[290] but their weakness makes them inappropriate for detection at low concentrations.

Fluorescence or luminescence can be used for detection. Fluorescence from the species of interest can be discriminated from background fluorescence using multispectral imaging.[6] Chemi- and bioluminescence have been used for selective detection of explosives.[286] The discrimination capabilities of enzyme reactions have been utilized in a bioluminescent sensor,[291] achieving 5 $\mu g/L$ detection limits for TNT and RDX. Visible luminescence has been observed from thermally decomposed nitro-organic vapors in a tube furnace.[292]

A. Fluorescing polymers

Recent developments utilize an indirect fluorescence method, i.e., quenching of fluorescence of a very strongly fluorescing material, to achieve very low detection limits.[293–297] The techniques utilize quenching of fluorescing or fluorescence amplifying polymers when a target molecule is attached. "Super quenching" is observed when a single target molecule is effective at quenching fluorescence from many polymer repeat units. McBranch and co-workers modified conjugated polymers using surfactants to increase selectivity and sensitivity towards nitroaromatics, achieving micromolar detection limits in solution.[293] Nomadics has used this effect to achieve femtogram detection limits of TNT in air,[297] the lowest detection limit for TNT to date. Modifications of the polymer materials to achieve selectivity for many different kinds of explosives would result in an excellent tool for screening and, perhaps, stand off detection using distributed sensors. Further studies on selectivity, matrix effects, and false positives are needed.

B. Color reactions

Perhaps the simplest of all methods discussed in this review, several kinds of color change chemical sensors have been developed for rapid on-site detection of explosives and their impurities and/or degradation products.[298–307] The reagents to produce the colored adduct have been contained in exchange resin matrices, polymeric membranes, and porous thin films which are incorporated into various fieldable devices. The color change has been recorded visually or with fiber optic based UV/visible absorption spectrometry or fluorescence quenching methods. Color reactions have also been developed for soil contamination screening methods. Heller *et al.* have achieved 100 ppb detection limit for TNT in water.[298] Jian and Seitz measured detection limits of 2 mg/L for TNT and DNT and 10 mg/L for RDX.[299] A commercial system using this technology is available as the EXPRAY Field Test Kit, with components appropriate for Group A explosives (nitroaromatics), Group B explosives (RDX, PETN, NG, etc.) and for inorganic nitrates.[307] Adaptation of this detection method to vapor detection via vapor sampling and preconcentration can be imagined, although the detection limits may be inadequate.

XI. IMMUNOCHEMICAL SENSORS

A very large number of immunochemical sensors have been developed for explosives, but most have been designed for environmental concerns such as in contamination in ground water or effluents from storage and testing facilities.[308–335] Although trace detection for screening applications has not been investigated in depth using these kinds of sensors, they have good potential as their analysis times have been significantly reduced recently. In immunochemical sensors, antigen-antibody complexes are formed for proteins containing the molecule of interest (i.e., an explosive).[2,308–310] When the substance binds to the antibody, a change in a physical property (e.g., absorption or fluorescence) can occur, which leads to a method of detection. Usually these immunosensors are operated under continuous flow conditions. Sometimes materials (usually plastic beads) containing the antibodies have been previously treated with a fluorescent dye-labeled explosive analog that is released to the solution when the explosive interacts with the antibody (referred to as competitive immunoassay). One commonly used method is the enzyme-linked immunosorbent assay (ELISA).[311–313] ELISA is based on the specificity of the antibody for the analyte and the resultant immune complex. The main development for application to explosives is deriving analyte specific antibodies to maximize the specificity and sensitivity for each target compound.

Immunochemical sensors can have incredible detection limits, sometimes in the ng/L range.[311–328] For example, Niessner *et al.* achieved 20 ng/L detection of TNT using ELISA[312] and VanBergen *et al.* measured 5μg/L detection limits for TNT and RDX using competitive fluorescent immunoassay.[315]

During the last decade, the continuous flow displacement immunosensor (CFI) has emerged as a rapid, sensitive, and portable assay format for the detection of explosives.[329–334] While similar to affinity chromatographic techniques, there is an important distinction. The performance of a displacement assay is heavily dependent on the dissociation kinetics between the labeled analyte and immobilized antibodies. CFIs offer certain advantages over competing technologies in low or medium throughput screening scenarios. After the initial preparation of the sensor, it is reagentless; there are no secondary reagents or incubation periods after sample injection. This leads to typical response times of less than 2 min, an improvement but still too long for passenger or other screening applications.

Very recently, Bromberg and Mathies have used homogeneous immunoassay as a detector for TNT and its analogs on a microfabricated CE chip, and found 1 ng/mL detection limits and 1–300 ng/mL dynamic range.[335]

XII. ELECTROCHEMICAL SENSORS

Electroanalytical methods include voltammetry $[i \neq 0; E=\mathrm{f}(t)]$, potentiometry $(i=0)$, amperometry $(i\neq 0; E=\mathrm{const})$, impedance or conductance, and combinations. Electrochemical cells can be divided into two classes: galvanic and electrolytic. Galvanic cells can operate continuously because the opposing electromotive force (emf) is absolutely less than the zero current potentiometric potential difference. Chemical energy is converted into electrical energy. The open circuit emf is the limiting value of the electric potential difference at zero current. An electrolytic cell is one in which chemical reactions are caused by applying an external potential difference (E) greater than, and opposite to, the galvanic emf of the cell. The zero current emf lies numerically between the decreasing cell potential differences during galvanic action and the absolutely larger applied potential differences required for electrolytic action.[336,337] Methods used for detection of explosives have been amperometry (TNT thermal degradation products[338,340]), cyclic voltammetry (TNT in environmental samples—Krausa *et al.*[341]), and square wave voltammetry (TNT in water—Wang *et al.*[342,344]) including disposable sensors. Using this method with screen-printed disposable carbon electrodes, Wang *et al.* have achieved <100 ppb detection of TNT;[343] interferences from other explosives as well as fertilizers are possible.

Wang *et al.* have also utilized a variety of electrochemical detection schemes as detectors for capillary electrophoresis or other separation methods on a chip.[345–347] Chip based methods have grown rapidly in importance, because of the increase in detection speed as well as their ability to be used *in situ* or in the field. Rapid growth in the number and kind of these devices is expected in the near future.

XIII. ELECTRONIC NOSE DEVICES

By combining multiple sensors (either nonselective or with sensitivity to different species or classes of chemicals) with pattern recognition, an artificial olfaction system can be produced.[349] A wide variety of multiple sensor types have been employed in this way for explosive sensing. Fluorescence amplifying polymers have been utilized, as discussed above. Walt *et al.* have loaded color reagents into microspheres and attached them to an imaging fiber or fiber bundle sensor that is trained computationally to recognize patterns characteristic of target compounds.[350] The system has successfully detected 120 ppb of DNT vapor in blind field tests.[351] Surface acoustic wave (SAW) resonances are shifted in frequency when a molecule becomes attached to the surface of a device.[352] These frequency changes can be detected with extreme sensitivity, enabling very low detection limits. The largest impediment for application of SAW devices has been one of selectivity. Therefore, they have been used as detectors following a separation step, as was discussed above under GC.[105] Various methods have been investigated to improve SAW device selectivity. For application to explosives detection, chemically modified polymers or other surface coatings have been used to provide increased selectivity and sensitivity by selectively and strongly binding the target molecule.[215] Optimized binding agents are being sought for each explosive material.[58]

Microelectromechanical systems (MEMS) have also been utilized in electronic nose explosives detectors. An array of microfabricated nano-cantilevers can be coated with different sensor materials. Adsorption of target molecules to the different sensor materials causes the relevant cantilevers to bend, which in turn causes the beam from a diode laser reflected from the cantilevers to move around on a quadrant photodiode detector. The pattern of responses caused by a target molecule is used to train the system.[353] Another group is using changes in the microcantilever vibrational resonance frequency as their temperature is scanned after loading the polymer coating by exposure to explosives vapor.[354] The different explosives thermally react at different temperatures (as in a differential scanning calorimeter), giving characteristic patterns, which are used to identify the materials.

XIV. DISCUSSION

There is still no “magic bullet” explosives detector to solve the simultaneous problems of speed, sensitivity, and selectivity required for, e.g., passenger screening, let alone the greater challenge of stand off detection for protection of personnel and property. However, there have been great advances in the past few years. The detection limits for TNT and its relatives are approaching femtogram levels. Nearly all technologies have portable or deployable embodiments. The number of research groups and spin-off companies is increasing. This trend provides a large measure of hope that the seemingly impossible goals may actually be achievable. Hopefully, the work reviewed here will assist bringing that process to a successful conclusion.

ACKNOWLEDGMENTS

This work was performed under the auspices of the United States Department of Energy National Nuclear Safety Administration. The author thanks Steven Son and David Funk for support.

GLOSSARY

Explosives

Amatol = mixtures of AN and TNT
AN = ammonium nitrate; NH_4NO_3
AP = ammonium perchlorate; NH_4ClO_4
ANFO = composition of ammonium nitrate and fuel oil
Comp A-3 = composition of RDX and heavy wax
Comp B = composition of 60% RDX and 40% TNT, sometimes with wax
Comp C-4 = composition of 91% RDX plus waxes and oils; a.k.a. C-4
Cyclotol = composition of 75% RDX and 25% TNT
DDNP = diazodinitrophenol; Dinol
DEGDN = diethyleneglycol dinitrate
Detasheet = composition of PETN and NC with plasticizers
DNB = 1,3-dinitrobenzene
EGDN = ethylene glycol dinitrate; nitroglycol
H-6 = composition of RDX and TNT with aluminum particles and wax
HBX-1 = composition of RDX and TNT with aluminum particles and wax
HMTD = hexamethylenetriperoxidediamine
HMX = octagen; octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine
HNS = hexanitrostilbene; 1, 1′-(1,2-ethenediyl)bis-[2,4,6-trinitrobenzene]
HNAB = hexanitro-azobenzene
LX-10 = PBX with HMX and bonding agent
LX-17 = PBX with TATB and bonding agent
MATB = monoamino-trinitro-benzene; ammonium picrate
NB = nitrobenzene
NC = nitrocellulose; gun cotton
NG = nitroglycerine; nitro; glyceryl trinitrate; RNG; trinitroglycerine
Octol = 75%HMX/25% TNT

PBX = plastic bonded explosive
PBX-9404 = PBX with HMX and energetic bonding agents
PBX-9501 = PBX with HMX, bonding agent, and plasticizers
PE 4 = British Comp C; RDX with waxes and/or heavy oils
PETN = pentaerythritol tetranitrate; 2,2-bis [(nitroxy)methyl]-1,3-propanediol, dinitrate
Picric acid = 2,4,6-trinitrophenol
Pentolite = composition of 50% PETN and 50% TNT
RDX = cyclonite; hexogen; hexahydro-1,3,5-trinitro-1,3,5-triazine
Semtex-H = composition of RDX and PETN with heavy oils and rubbers
TATB = trinitro-triamino-benzene; 2,4,6-trinitro-1,3,5-benzene-triamine
TATP = triacetone triperoxide
Tetryl = methyl-2,4,6-trinitrophenylnitramine
TEGDN = triethyleneglycol dinitrate
TNB = 1,3,5-trinitrobenzene
TNT = 2,4,6-trinitrotoluene; 2-methyl-1,3,5-trinitro-benzene
Tritonal = aluminized TNT

Instrumentation

API = atmospheric pressure ionization
ASGDI = atmospheric sampling glow discharge ion trap mass spectrometer
CBW = chemical/biological weapon
CCD = charged coupled device
CE = capillary electrophoresis
CFI = continuous flow displacement immunosensor
CRDS = cavity ring down spectroscopy
ECD = electron capture detector
ECNIMS = electron-capture negative ion mass spectrometer
ELISA = enzyme-linked immunosorbent assay
GC = gas chromatography
HPLC = high performance liquid chromatography
ITMS = ion trap MS
LIDAR = light detection and ranging
LSPR = localized surface plasmon resonance
MEMS = microelectromechanical systems
REMPI = resonance enhanced multiphoton ionization
READ = reversal electron attachment mass spectrometer
SAW = surface acoustic wave
SERS = surface enhanced Raman scattering
SFE = supercritical fluid extraction
SPE = solid phase extraction
SPME = solid phase microextraction
TEA = thermal energy analyzer
UVRRS = ultraviolet resonance Raman scattering

[1] D. S. Moore, Los Alamos Report LAUR-03-1665 (2003).

[2] J. Yinon, Trends Analyt. Chem. **21**, 292 (2002).

[3] C. Bruschini, ExploStudy, Final Report, Ecole Polytechnique Federale de Lausanne, Web URL: http://diwww.epfl.ch/lami/detec/ (2001).

[4] E. T. Urbansky, Crit. Rev. Anal. Chem. **30**, 311 (2000).

[5] J. Yinon, *Forensic and Environmental Detection of Explosives* (Wiley, Chichester, 1999).

[6] J. I. Steinfeld and J. Wormhoudt, Annu. Rev. Phys. Chem. **49**, 203 (1998).

[7] J. Yinon and S. Zitrin, *Modern Methods and Applications in Analysis of Explosives* (Wiley, Chichester, 1993).

[8] M. R. Nyden, *A Technical Assessment of Portable Explosives Vapor Detection Devices, NIJ Rep. 300-89* (NIST, Gaithersburg, MD, 1990).

[9] J. Yinon, Crit. Rev. Anal. Chem. **7**, 1 (1977).

[10] R. Tiron, National Defense July 2003, 20–21 (2003).

[11] Federal Register, 67, No. 81, 20864–20866 (2002).

[12] B. C. Dionne, D. P. Rounbehler, E. K. Achter, J. R. Hobbs, and D. H. Fine, J. Energetic Mat. **4**, 447 (1986).

[13] R. Haas, ″Stoffdatenblätter wichtiger Explosivstoffe.” Web URL: http://haasr.freeyellow.com/vl7.html

[14] J. C. Oxley. Proc. SPIE **2511**, 217 (1995).

[15] P. Kolla. Angew. Chem., Int. Ed. Engl. **36**, 800 (1997).

[16] W. R. Davidson, W. R. Stott, R. Sleeman, and A. K. Akery, Proc. SPIE **2092**, 108 (1994).

[17] D. J. Phares, J. K. Holt, G. T. Smedley, and R. C. Flagan, J. Forensic Sci. **45**, 774 (2000).

[18] G. L. Gresham *et al.*, Proc. SPIE **2276**, 34–44 (1994).

[19] Accustandards Inc. Web URL www.accustandard.com

[20] Absolute Standards, Inc. Web URL www.absolutestandards.com

[21] EPA Method 8330, Web URL: www.epa.gov/epaoswer/hazwaste/test/pdfs/8330.pdf

[22] C. L. Rhykerd, D. W. Hannum, D. W. Murray, and J. E. Parmeter, “Guide for the Selection of Commercial Explosives Detection Systems for Law Enforcement Applications,” NIJ Guide 100-99, National Institute of Justice, Office of Science and Technology, Washington, DC 20531, September 1999, NCJ 178913. Web: http://virlib.ncjrs.org/LawEnforcement.asp or directly http://www.ncjrs.org/pdffilesl/nij/178913-1 pdf and http://www.ncjrs.org/pdffilesl/nij/178913-2.pd

[23] Assessment of Technologies Deployed to Improve Aviation Security: First Report (1999) US National Academy of Sciences Commission on Engineering and Technical Systems (CETS). Web: http://www.nap.edu/books/0309067871/html/3.html

[24] Committee on Commercial Aviation Security. 1997, Second Interim Rep. Fed. Aviat. Admin. Tech. Cent., DOT/FAA/AR-97/57.

[25] M. Fischetti, Technol. Rev. **100**, 39 (1997).

[26] W. H. Makky, ed., *Proc. Explosives Detection Technology Symp. Aviation Security Technology Conf. 2nd*, Atlantic City, FAA (1996).

[27] C. R. Midkiff and R. E. Tontarski, Jr., Detection and Characterization of Explosives and Explosive Residues-A Review Int. ICPO-INTERPOL Forensic Sci. Symp., 11th Lyons (1995).

[28] A. M. Rouhi, Chem. Eng. News **73**, 10 (1995).

[29] G. Vourvopoulos, Chem. Ind. **1994**, 297 (1994).

[30] A. Fainberg, Science **255**, 1531 (1992).

[31] J. Yinon, ed., *Proc. Int. Symp. Anal. Detect. Explos., 4th*, London (Kluwer, Dordrecht, 1992).

[32] G. J. Wendel, E. E. A. Bromberg, and M. K. Durfee, in *Proc. Symp. Explosives Detection Technology 2nd*, edited by W. H. Makky, Atlantic City, FAA (1996), pp. 181–186.

[33] G. S. Settles, H. A. Gowadia, S. B. Strine, and T. E. Johnson, *ibid.*, pp. 65–70.

[34] J. E. Parmeter, K. L. Linker, C. L. Rhykerd, Jr., and D. W. Hannum, pp. 187–192.

[35] A. Mercado and P. Marsden, *Proc. Int. Workshop on Ion Mobility Spectrometry*, NASA Conf. Publ. 3301 (1995), pp. 168–89.

[36] J. T. Arnold, Proc. SPIE **2276**, 412 (1994).

[37] W. McGann, A. Jenkins, and K. Ribeiro, in *Proc. Int. Symp. Explosive Detection Technology, 1st*, Atlantic City, FAA (1992), pp. 518–531.

[38] D. H. Fine and E. K. Achter, *Symposium on Access Security Screening: Challenges and Solutions, New Orleans, LA, ASTM Spec. Tech. Publ. 1127* (ASTM, Philadelphia, l992), pp. 45–49.

[39] E. K. Achter, G. Miskolczy, F. W. Fraim, E. Hainsworth, and J. R. Hobbs, in *Proc. Int. Symp. Explosive Detection Technology, 1st*, Atlantic City, FAA (1992), pp. 427–434.

[40] P. Z. Jankowski, A. G. Mercado, and S. F. Hallowell, Proc. SPIE **1824**, 13 (1993).

[41] D. H. Fine and G. J. Wendel, Proc. SPIE **2092**, 131 (1994).

[42] T. G. Sheldon, R. J. Lacey, G. M. Smith, P. J. Moore, and L. Head, Proc. SPIE **2092**, 145 (1994).

[43] R. K. Ritchie, P. C. Thomson, R. F. DeBono, L. L. Danylewych-May, and L. Kim, Proc. SPIE **2092**, 87 (1994).

[44] G. Bennett, R. Sleeman, W. R. Davidson, and W. R. Stott, Proc. SPIE **2276**, 363 (1994).

[45] S. Nacson, O. Legrady, T. Siu, D. Greenberg, S. Nargolwalla, and P. Geblewicz, Proc. SPIE **2276**, 69 (1994).

[46] F. W. Fraim, E. K. Achter, A. L. Carroll, and E. Hainsworth, in *Proc. Int. Symp. Explosive Detection Technology, 1st*, Atlantic City, FAA (1992), pp. 559–570.

[47] A. Jenkins, W. McGann, K. Ribeiro, *ibid.*, pp. 532–551.

[48] E. E. A. Bromberg, A. L. Carroll, F. W. Fraim, and D. P. Lieb, *ibid.*, pp. 552–558.

[49] J. R. Hobbs and E. P. Conde, in *Proc. Int. Symp. Anal. Detect. Explos, 4th*, London (Kluwer, Dordrecht, 1992), pp. 437–453.

[50] E. Bender, A. Hogan, D. Leggett, G. Miskolczy, and S. MacDonald, J. Forensic Sci. **37**, 1673 (1992).

[51] B. Y. H. Liu, S. H. Yoo, J. P. Davies, G. Gresham, and S. F. Hallowell, Proc. SPIE **2276**, 45 (1994).

[52] F. J. Conrad, Nucl. Mater. Managem. **13**, 212 (1984).

[53] F. W. Fraim, E. K. Achter, A. L. Carroll, and E. Hainsworth, in *First International Symposium on Explosive Detection Technology*, Atlantic City, NJ (1991), pp. 559–570.

[54] S. Nacson, in *Fifth International Symposium on Analysis and Detection of Explosives*, Washington, DC (1995), paper no. 41.

[55] P. Neudorfl, M. A. McCooeye, and L. Elias, in *Advances in Analysis and Detection of Explosives*, edited by J. Yinon (Kluwer Academic, Dordrecht, 1993), pp. 373–384.

[56] W. R. Davidson, W. R. Stott, R. Sleeman, and A. K. Akery, in *Conference on Substance Detection Systems*, Innsbruck, Austria, 1993. Proc. SPIE 2092, 108 (1994).

[57] E. Psillakis and N. Kalogerakis, J. Chromatogr., A **907**, 211 (2001).

[58] E. J. Houser, T. B. Mlsna, V. K. Nguyen, R. Chung, R. L. Mowery, and R. A. McGill, Talanta **54**, 469 (2001).

[59] D. C. Stahl and D. C. Tilotta, Environ. Sci. Technol. **35**, 3507 (2001).

[60] K. G. Furton, J. R. Almirall, M. Bi, J. Wang, and L. Wu, J. Chromatogr., A **885**, 419 (2000).

[61] S. F. Hallowell, Talanta **54**, 447 (2001).

[62] D. C. Seward and T. Yukl, in *First International Symposium on Explosive Detection Technology*, Atlantic City, NJ (1991), pp. 441–453.

[63] D. C. Seward and T. Yukl, in *Second Explosives Detection Technology Symposium & Aviation Security Technology Conference*, Atlantic City, NJ (1996), pp. 162–169.

[64] C. Rhykerd, K. Linker, D. Hannum, and J. Parmeter, Nucl. Mater. Managem. **26**, 97 (1997).

[65] G. J. Wendel, E. E. A. Bromberg, M. K. Durfee, and W. Curby, in *Second Explosives Detection Technology Symposium & Aviation Security Technology Conference*, Atlantic City, NJ (1996), pp. 181–186.

[66] J. E. Parmeter, K. L. Linker, C. L. Rhykerd, Jr., and D. W. Hannum, *ibid.*, pp. 187–192.

[67] J. R. Hobbs and E. P. Conde, in *Advances in Analysis and Detection of Explosives*, edited by J. Yinon (Kluwer Academic, Dordrecht, 1993), pp. 437–453.

[68] E. E. A. Bromberg, D. Dussault, S. MacDonald, and W. A. Curby, *ibid.*, pp. 473–484.

[69] M. M. Hintze, B. L. Hansen, and R. L. Heath, in *First International Symposium on Explosive Detection Technology*, Atlantic City, NJ (1991), pp. 634–636.

[70] A. Jenkins, W. McGann, and K. Ribeiro, *ibid.*, pp. 532–551.

[71] G. A. Eiceman, C. M. Boyett, and J. E. Parmeter, National Institute of Justice Report 100-99, NCJ 178261 (1999).

[72] P. Kol1a, Anal. Chem. **67**(5), 184A (1995).

[73] G. A. Eiceman, D. Preston, G. Tiano, J. Rodriguez, and J. E. Parmeter, Talanta **45**, 57 (1997).

[74] M. G. Hartell, L. J. Myers, P. Wagonner, M. Kuhiman, S. F. Hallowell, and J. A. Petrousky, in *Fifth International Symposium on Analysis and Detection of Explosives*, Washington, DC, 1995, Paper No. 48.

[75] M. G. Hartell, M. Q. Pierce, L. J. Myers, S. F. Hallowell, and J. A. Petrousky, *ibid.*, Paper No. 46.

[76] W. R. Stott, D. Green, and A. Mercado, in *Conference on Cargo Inspection Technologies*, San Diego, CA, 1994. SPIE Proc. 2276, 87 (1994).

[77] D. P. Lucero, S. R. Roder, P. Jankowski, and A. Mercado, in *Advances in Analysis and Detection of Explosives*, edited by J. Yinon (Kluwer Academic, Dordrecht, 1993), pp. 485–502.

[78] J. P. Davies, L. G. Blackwood, S. G. Davis, L. D. Goodrich, and R. A. Larsen, *ibid.*, pp. 513–532.

[79] J. P. Davies, L. G. Blackwood, S. G. Davis, L. D. Goodrich, and R. A. Larson, Anal. Chem. **65**, 3004 (1993).

[80] E. E. A. Bromberg, D. Dussault, S. MacDonald, and W. A. Curby, in *Proc. Int. Symp. Anal. Detect. Explos., 4th*, London (Kluwer, Dordrecht, 1992), pp. 473–484.

[81] B. T. Kenna, F. J. Conrad, and D. W. Hannum, in *Proc. Int. Symp. Explosive Detection Technology, 1st*, Atlantic City, FAA (1992), pp. 510–517.

[82] S. J. Macdonald and D. P. Rounbehler, *ibid.*, pp. 584–588.

[83] G. A. Reiner, C. L. Heisy, and H. M. McNair, J. Energ. Mater. **9**, 173–190 (1991).

[84] J. P. Davies, S. F. Hallowell, and D. E. Hoglund, Proc. SPIE **2092**, 137 (1994).

[85] L. Elias, J. Test. Eval. **22**, 280 (1994).

[86] P. Neudorfl, M. A. McCooeye, and L. Elias, in *Proc. Int. Symp. Anal. Detect. Explos., 4th* (Kluwer, Dordrecht, London, 1992), pp. 373–384.

[87] M. Williams, J. M. Johnston, L. P. Waggoner, J. Jackson, M. Jones, T. Boussom, S. F. Hallowell, and J. A. Petrousky, *Second Explosives Detection Technology Symposium & Aviation Security Technology Conference*, Atlantic City, NJ (1996), pp. 328–339.

[88] G. B. Biederman, in *Advances in Analysis and Detection of Explosives*, edited by J. Yinon (Kluwer Academic, Dordrecht, 1993), pp. 463–472.

[89] U. A. Luescher, J. Am. Vet. Med. Assoc. **203**, 1538 (1993).

[90] S. Lovett, *First International Symposium on Explosive Detection Technology*, Atlantic City, NJ (1991), pp. 774–775.

[91] J. W. Ternes, *ibid.*, pp. 891–902.

[92] S. Weinstein, R. Drozdenko, and C. Weinstein, *Third International Symposium on Analysis and Detection of Explosives*, Mannheim-Neuostheim, Germany (1989), pp. 32.31–32.34.

[93] R. H. Wright, *The Sense of Smell* (CRC, Boca Raton, 1982), p. 236.

[94] *National Defense Magazine*, June 2003, p. 8.

[95] M. Williams, J. M. Johnston, M. Cicoria, E. Paletz, L. P. Waggoner, C. C. Edge, and S. F. Hallowell, Proc. SPIE **3575**, 291 (1998).

[96] N. Lorenzo, T. L. Wan, R. J. Harper, Y. L. Hsu, M. Chow, S. Rose, and K. G. Furton, Anal. Bioanal. Chem. **376**, 1212 (2003).

[97] K. G. Furton and L. J. Myers, Talanta **54**, 487 (2001).

[98] R. Batlle, H. Carlsson, P. Tollbäck, A. Colmsjö, and C. Crescenzi, Anal. Chem. **75**, 3137 (2003).

[99] T. Weiss and J. Angerer, J. Chromatog. B **778**, 179 (2002).

[100] C. A. Groom, S. Beaudet, A. Halasz, L. Paquet, and J. Hawari, J. Chromatogr., A **909**, 53 (2001).

[101] A. Gordin and A. Amirav, J. Chromatogr., A **903**, 155 (2000).

[102] M. E. Sigman and C. Y. Ma, J. Forensic Sci. **46**, 6 (2001).

[103] M. E. Walsh, Talanta **54**, 427 (2001).

[104] M. E. Sigman and C. Y. Ma, Anal. Chem. **71**, 4119 (1999).

[105] E. J. Staples and G. W. Watson, *Pittsburgh Conference on Analytical Chemistry and Applied Spectroscopy*, New Orleans, LA, Paper No. 1583CP (1998).

[106] H. Ertl, U. Breit, H. Kaltschmidt, and H. Oberpriller, Proc. SPIE **2276**, 58 (1994).

[107] P. M. Holland *et al.*, Proc. SPIE **2276**, 79 (1994).

[108] J. R. Hobbs and E. P. Conde, *Proc. Int. Symp. Anal. Detect. Explos., 4th*, London (Kluwer, Dordrecht, 1992), pp. 153–164.

[109] P. Kolla, J. Chromatogr. A **674**, 309 (1994).

[110] D. A. Palmer, E. K. Achter, and D. Lieb, Proc. SPIE **1824**, 109 (1993).

[111] S. Fox and T. Hooley, Proc. SPIE **2093**, 195 (1994).

[112] S. Nacson, L. McNelles, S. Nargolwalla, and D. Greenberg, *Second Explosives Detection Technology Symposium & Aviation Security Technology Conference*, Atlantic City, NJ (1996), pp. 38–48.

[113] D. H. Fine, D. Lieb, and F. Rufeh, J. Chromatogr. **107**, 351 (1975).

[114] A. L. Lafleur and K. M. Mills, Anal. Chem. **53**, 1202 (1981).

[115] E. U. Goff, W. C. Yu, and D. H. Fine, *International Symposium on Analysis and Detection of Explosives*, Quantico, VA (1983), pp. 159–168.

[116] D. P. Rounbehler, S. J. MacDonald, D. P. Lieb, and D. H. Fine, *First International Symposium on Explosive Detection Technology*, Atlantic City, NJ (1991), pp. 703–713.

[117] H. Wohltjen and R. Dessy, Anal. Chem. **51**, 1458 (1979).

[118] H. Wohltjen and R. Dessy, Anal. Chem. **51**, 1465 (1979).

[119] G. Watson, W. Horton, and E. Staples, *First International Symposium on Explosive Detection Technology* Atlantic City, NJ (1991), pp. 589–603.

[120] R. Schulte-Ladbeck, P. Kolla, and U. Karst, Anal. Chem. **75**, 731 (2003).

[121] C. E. Wissinger and B. R. McCord, J. Forensic Sci. **47**, 168 (2002).

[122] A. Schreiber, J. Efer, and W. Engewald. J. Chromatogr., A **869**, 411 (2002).

[123] R. Batlle, H. Carlsson, E. Holmgren, A. Colmsjo, and C. Crescenzi, J. Chromatogr., A **963**, 73 (2002).

[124] M. J. Lang and S. E. Burns, J. Chromatogr., A **849**, 381 (1991).

[125] L. M. Wu, J. R. Almirall, and K. G. Furton, J. High Resolut. Chromatogr.

22, 279 (1999).

[126] B. R. McCord, K. A. Hargadon, K. E. Hall, and S. G. Burmeister, Anal. Chim. Acta **288**, 43 (1994).

[127] J. Wang, M. Pumera, M. P. Chatrathi, A. Escarpa, and M. Musameh, Anal. Chem. **74**, 1187 (2002).

[128] J. Wang, M. Pumera, G. Collins, F. Opekarc, and I. Jelinekc, Analyst (Cambridge, U.K.) **127**, 719 (2002).

[129] W. Thormann, I. S. Lurie, B. McCord, U. Marti, B. Chenni, and N. Malik, Electrophoresis **22**, 4216 (2001).

[130] J. C. Mathurin, T. Faye, A. Brunot, and J. C. Tabet, Anal. Chem. **72**, 5055 (2000).

[131] L. S. Riter, D. F. Fraley, and R. G. Cooks, J. Am. Soc. Mass Spectrom. **11**, 33 (2000).

[132] S. M. Hankin *et al.*, Rapid Commun. Mass Spectrom. **16**, 111 (2002).

[133] Z. G. Wu, C. L. Hendrickson, R. P. Rodgers, and A. G. Marshall, Anal. Chem. **74**, 1879 (2002).

[134] C. S. Evans, R. Sleeman, J. Luke, and B. J. Keely, Rapid Commun. Mass Spectrom. **16**, 1883 (2002).

[135] J. Costanza and W. M. Davis, Field Anal. Chem. Technol. **4**, 246 (2000).

[136] D. A. Cassada, S. J. Monson, D. D. Snow, and R. F. Spalding, J. Chromatogr., A **844**, 87 (1999).

[137] Y. McAvoy, K. Dost, D. C. Jones, M. D. Cole, M. W. George, and G. Davidson, Forensic Sci. Int. **99**, 123 (1999).

[138] C. A. McDowell, *Mass Sprectrometry* (McGraw Hill, New York, 1963).

[139] J. N. Loans, R. G. Cooks, J. E. P. Syka, P. E. Kelley, G. C. Stafford, Jr., and J. F. J. Todd, Anal. Chem. **59**, 1677 (1987).

[140] R. G. Cooks, O. L. Glish, S. A. McLuckey, and R. E. Kaiser, Chem. Eng. News **1991**, 26–41 (1991).

[141] F. W. McLafferty, Science **214**, 280 (1981).

[142] J. Yinon, in *Forensic Science Progress*, edited by A. Maehly and R. L. Williams (Springer, Heidelberg, 1991), Vol. 15, 1–29.

[143] R. A. Yost and C. G. Enke, Anal. Chem. **51**, 1251A (1979).

[144] S. T. Quarmby and R. A. Yost, US Patent No. 5,837,030, 15 April 1997.

[145] J. Yinon, J. E. McClellan, and R. A. Yost, Rapid Commun. Mass Spectrom. **11**, 1961 (1997).

[146] W. R. Davidson, B. A. Thomson, A. K. Akery, and R. Sleeman, in *First International Symposium on Explosive Detection Technology*, Atlantic City, NJ (1991), pp. 653–662.

[147] W. R. Davidson, W. R. Stott, A. K. Akery, and R. Sleeman, *ibid.*, pp. 663–671.

[148] R. Sleeman, G. Bennett, W. R. Davidson, and W. Fisher, in *International Symposium on Contraband and Cargo Inspection Technologies*: Washington, DC (1992), pp. 57–63.

[149] W. R. Stott, W. R. Davidson, and R. Sleeman, Proc. SPIE **2092**, 53 (1994).

[150] G. Bennett, R. Sleeman, W. R. Davidson, and W. R. Stott, Proc. SPIE **2276**, 363 (1994).

[151] S. A. McLuckey, G. L. Glish, K. G. Asano, and B. C. Grant, Anal. Chem. **60**, 2220 (1988).

[152] S. A. McLuckey, G. L. Gush, and K. G. Asano, Anal. Chim. Acta **225**, 25 (1989).

[153] A. Chutjian and M. R. Darrach, in *Second Explosives Detection Technology Symposium & Aviation Security Technology Conference*, Atlantic City, NJ (1996), pp. 176–180.

[154] J. Yinon, H. G. Boettger, and W. P. Weber, Anal. Chem. **44**, 2235 (1972).

[155] J. Yinon and H. G. Boettger, Int. J. Mass Spectrom. Ion Phys. **10**, 161 (1972/73).

[156] J. A. Laramee, C. A. Kocher, and M. L. Deinzer, Anal. Chem. **64**, 2316 (1992).

[157] J. A. Laramee, R. B. Cody, W. B. Herrmannsfeldt, and M. L. Deinzer, in *44th ASMS Conference on Mass Spectrometry and Allied Topics*, Portland, OR (1996), p. 71.

[158] J. A. Laramee and M. L. Deinzer, in *Fifth International Symposium on Analysis and Detection of Explosives*, Washington, DC (1995), Paper No. 49.

[159] W. R. Davidson, W. R. Stott, A. K. Akery, and R. Sleeman, in *Proc. Int. Symp. Explosive Detection Technology, 1st*, Atlantic City, FAA (1992), pp. 663–671.

[160] J. Yinon, Mass Spectrom. Rev. **1**, 257 (1982).

[161] E. P. Burrows, in *Proc. Int. Symp. Anal. Detect. Explos., 4th*, London. (Kluwer, Dordrecht, 1992), pp. 299–307.

[162] T. H. Chen, *ibid.*, pp. 385–401.

[163] S. Boumsellek, S. H. Alajajian, and A. Chutjian. J. Am. Soc. Mass Spectrom. **3**, 243 (1992).

[164] S. Boumsellek and A. Chutjian, Anal. Chem. **64**, 2096 (1992).

[165] A. Chutjian, S. Boumsellek, and S. H. Alajajian, in *Proc. Int. Symp. Explosive Detection Technology, 1st*, Atlantic City, FAA (1992), pp. 571–583.

[166] W. R. Davidson, B. A. Thomson, T. Sakuma, W. R. Stott, A. K. Akery, and R. Sleeman, *ibid.*, pp. 653–662.

[167] A. Chutjian and M. R. Darrach, in *Proc. Explosive Detection Technology Symp. Aviation Security Technology Conf., 2nd*, Atlantic City, FAA (1996), pp. 176–180.

[168] A. D. Wright, K. R. Jennings, and R. Peters, in *Proc. Int. Symp. Anal. Detect. Explos., 4th*, London (Kluwer, Dordrecht, 1992), pp. 291–298.

[169] Y. Xu and J. A. Herma, Rapid Commun. Mass Spectrom. **6**, 425 (1992).

[170] C. S. Giam, M. S. Ahmed, R. R. Weller, and J. Derrickson, in *Proc. Int. Symp. Explosive Detection Technology, 1st*, Atlantic City, FAA (1992), pp. 687–688.

[171] C. S. Giam, T. L. Holliday, M. S. Ahmed, G. E. Reed, and G. Zhao, Proc. SPIE **2092**, 227 (1994).

[172] M. L. Langford and J. F. J. Todd, Org. Mass Spectrom. **28**, 773 (1993).

[173] K. C. Crellin, M. Widmer, and J. L. Beauchamp, Anal. Chem. **69**, 1092 (1997).

[174] W. R. Stott, D. Green, and A. Mercado, Proc. SPIE **2276**, 87 (1994).

[175] A. Cappiello, G. Famiglini, A. Lombardozzi, A. Massari, and G. G. Vadalia, J. Am. Soc. Mass Spectrom. **7**, 753 (1996).

[176] J. Zhao, J. Zhu, and D. M. Lubman, Anal. Chem. **64**, 1426 (1992).

[177] S. D. Huang, L. Kolaitis, and D. M. Lubman, Appl. Spectrosc. **41**, 1371 (1987).

[178] W. A. Bryden, R. C. Benson, S. A. Ecelberger, T. E. Phillips, T. Cornish, and R. J. Cotter, Proc. SPIE **2511**, 153 (1995).

[179] G. L. Glish, S. A. McLuckey, B. C. Grant, and H. S. McKown, in *Proc. Int. Symp. Explosive Detection Technology, Ist*, Atlantic City, FAA (1992), pp. 642–652.

[180] K. G. Asano, D. E. Goeringer, and S. A. McLuckey, Anal. Chem. **67**, 2739 (1995).

[181] S. A. McLuckey, D. E. Goeringer, K. G. Asano, G. Vaidyanathan, and J. L. Stephenson, Jr., Rapid Commun. Mass Spectrom. **10**, 287 (1996).

[182] H. G. Lee, E. D. Lee, and M. L. Lee, *Proc. Int. Symp. Explosive Detection Technol., 1st*, edited by S. M. Khan, Atlantic City, FAA (1992), pp. 619–633.

[183] R. G. Ewing, D. A. Atkinson, G. A. Eiceman, and G. J. Ewing, Talanta **54**, 515 (2001).

[184] D. C. Collins and M. L. Lee, Anal. Bioanal. Chem. **372**, 66 (2002).

[185] H. H. Hill and G. Simpson, Field Anal. Chem. Technol. **1**, 119 (1997).

[186] G. A. Eiceman, TrAC, Trends Anal. Chem. **21**, 259 (2002).

[187] T. Khayamian, M. Tabrizchi, and M. T. Jafari, Talanta **59**, 327 (2003).

[188] C. Wu, W. E. Steiner, P. S. Tornatore, L. M. Matz, W. F. Siems, D. A. Atkinson, and H. H. Hill, Talanta **57**, 123 (2002).

[189] A. K. Knight, R. P. Sperline, G. M. Heiftje, E. Young, C. J. Barinaga, D. W. Koppenaal, and M. B. Denton, Int. J. Mass. Spectrom. **215**, 131 (2002).

[190] G. A. Buttigieg, A. K. Knight, S. Denson, C. Pommier, and M. B. Denton, Forensic Sci. Int. **135**, 53 (2003).

[191] M. T. Griffin, J. E. Fulton, R. F. McAtee, R. Gao, and L. Tsoukalas, SPIE **5085**, 37 (2003).

[192] F. Li, Z. Xie, H. Schmidt, S. Sielemann, and J. I. Baumbach, Spectrochim. Acta, Part B **57**, 1563 (2002).

[193] M. Tabrizchi and A. Abedi, Int. J. Mass. Spectrom. **218**, 75 (2002).

[194] G. R. Asbury, J. Klasmeier, and H. H. Hill, Talanta **50**, 1291 (2000).

[195] G. A. Eiceman, D. Preston, G. Tiano, J. Rodriguez, and J. E. Parmeter, Talanta **45**, 57 (1997).

[196] F. Garafolo, V. Migliozzi, and B. Roio, Rapid Commun. Mass Spectrom. **8**, 527 (1994).

[197] Z. Karpas, Forensic Sci. Rev. **1**, 103 (1989).

[198] R. H. St. Louis and H. H. Hill, Jr., Crit. Rev. Anal. Chem. **21**, 321 (1990).

[199] D. D. Fetterolf and T. D. Clark, J. Forensic Sci. **38**, 28 (1993).

[200] L. L. Danylewych-May and C. Cumming, in *Advances in Analysis and Detection of Explosives*, edited by J. Yinon (Kluwer Academic, Dordrecht, 1993), pp. 385–401.

[201] Application Note No. 9702, FemtoScan Corporation, 1998. Web URL: http://femtoscan.com/analcap.htm

[202] R. K. Ritchie, F. Kuja, R. A. Jackson, A. J. Loveless, and L. L. Danylewych-May, Proc. SPIE **2092**, 76 (1994).

[203] D. D. Fetterolf and T. D. Clark, in *Proc. Int. Symp. Explosive Detection Technology, 1st*, Atlantic City, FAA (1992), pp. 689–702.

[204] D. D. Fetterolf, in *Proc. Int. Symp. Anal. Detect. Explos., 4th*, London

(Kluwer, Dordrecht, 1992), pp. 117–131.

[205] D. D. Fetterolf, B. Donnelly, and L. D. Lasswell, Proc. SPIE **2092**, 40 (1994).

[206] S. F. Hallowell, J. P. Davies, and B. L. Gresham, Proc. SPIE **2276**, 437 (1994).

[207] W. J. McGann, A. Jenkins, K. Ribiero, and J. Napoli, Proc. SPIE **2092**, 64 (1994).

[208] W. J. McGann, V. Bradley, A. Borsody, and S. Lepine, Proc. SPIE **2276**, 424 (1994).

[209] A. H. Lawrence, R. A. Goubran, and H. M. Hafez, Proc. SPIE **1824**, 97 (1993).

[210] L. L. Danylewych-May, in *Proc. Int. Symp. Explosive Detection Technology, 1st*, Atlantic City, FAA (1992), pp. 672–686.

[211] G. Simpson *et al.*, J. High Resolut. Chromatogr. **19**, 301 (1996).

[212] B. L. Carnahan, S. Day, V. Kouznetsov, and A. Tarassov, Proc. SPIE **2937**, 106 (1997).

[213] I. A. Buryakov, Y. N. Kolomiets, and B. V. Luppu, J. Anal. Chem. USSR **56**, 336 (2001).

[214] I. A. Buryakov, Y. N. Kolomiets, and B. V. Luppu, *Proc. 8 Int. Conf. on IMS*, UK, Buxton (1999).

[215] X. G. Yang, X. X. Du, J. X. Shi, and B. I. Swanson, Talanta **54**, 439 (2001).

[216] J. Janni, B. D. Gilbert, R. W. Field, and J. I. Steinfield, Spectrochim. Acta, Part A **53**, 1375 (1997).

[217] Y. S. Tung, R. Mu, D. O. Henderson, and W. A. Curby, Appl. Spectrosc. **51**, 171 (1997).

[218] M. Clapper, J. Demirgian, and G. Robitaille, Spectroscopy **10**, 44 (1996).

[219] H. Riris, C. B. Carlisle, D. F. McMillen, and D. E. Cooper, Appl. Opt. **35**, 4694 (1996).

[220] J. Wormhotud *et al.*, Appl. Opt. **35**, 3992 (1996).

[221] T. Rohe, E. Grunblatt, and N. Eisenreich, *Proc. Int. Annu. Conf. Fraunhofer Inst. Chem. Technol* (1996), pp. 85-1–85-10.

[222] D. O. Henderson, E. Silberman, N. Chen, and F. W. Snyder, Appl. Spectrosc. **47**, 528 (1993).

[223] D. O. Henderson, R. Mu, Y. S. Tung, and G. C. Huston, Appl. Spectrosc. **49**, 444 (1995).

[224] A. Mercado and J. P. Davies, Proc. SPIE **2092**, 27 (1994).

[225] D. O. Henderson, E. Silberman, and F. W. Snyder, in *First International Symposium on Explosive Detection Technology*, Atlantic City, NJ (1991), pp. 604–617.

[226] F. Pristera, M. Halik, A. Castelli, and W. Fredericks, Anal. Chem. **32**, 495 (1960).

[227] D. E. Chasan and G. Norwitz, Microchem. J. **17**, 31 (1972).

[228] Z. Iqbal, K Suryanarayanan, S. Bulusu, and J. R. Autera, *Infrared and Raman Spectra of 1,3,5-trinitro-1,3,5-triazacyclohexane (RDX), Rep. AD-752899*, US Army Picatinny Arsenal, Dover, NJ (1972).

[229] N. Eisenreich, H. Kull, and J. Hertz, *Proc. Int. Annu. Conf. Fraunhofer Inst. Chem. Technol* (1994), pp. 86–1–86–7.

[230] D. Cavagnat, L. Lespade, and C. Lapouge, J. Chem. Phys. **103**, 10502 (1995).

[231] P. C. Claspy, Y.-H. Pao, S. Kwong, and E. Novov, Appl. Opt. **15**, 1506 (1977).

[232] R. J. Karpowicz and T. B. Brill, J. Phys. Chem. **88**, 348 (1984).

[233] W. R. Carper and J. J. P. Stewart, Spectrochim. Acta, Part A **43**, 1249 (1987).

[234] A. W. Stelson, S. K. Friedlander, and J. H. Seinfeld, Atmos. Environ. **13**, 369 (1979).

[235] A. W. Stelson and J. H. Seinfeld, Atmos. Environ. **16**, 983 (1982).

[236] T. Z. Hong, C. P. Tang, and K. Lin, in *Proc. Int. Symp. Anal. Detect. Explos., 4th*, London (Kluwer, Dordrecht, 1992), pp. 145–152.

[237] J. Wormhoudt, P. L. Kebabian, and C. E. Kolb, Combust. Flame **111**, 73 (1997).

[238] H. Riris, C. B. Carlisle, D. F. McMillen, and D. E. Cooper, Appl. Opt. **35**, 4694 (1996).

[239] D. D. Nelson, M. S. Zahniser, J. B. McManus, J. H. Shorter, J. Wormhoudt, and C. E. Kolb, Proc. SPIE **2834**, 148 (1996).

[240] J. Wormhoudt, M. S. Zahniser, D. D. Nelson, J. B. McManus, R. C. Miake-Lye, and C. E. Kolb, Proc. SPIE **2546**, 552 (1995).

[241] M. S. Zahnizer, D. D. Nelson, J. B. McManus, and P. L. Kebabian, Philos. Trans. R. Soc. London, Ser. A **351**, 371 (1995).

[242] S. Hnatnicky, J. Test. Eval. **22**, 282 (1984).

[243] D. H. Fine, D. P. Rounbehler, and W. A. Curby, in *Proc. Int. Symp Explosive Detection Technology, 1st*, Atlantic City, FAA (1992), 505–517.

[244] F. J. Lovas and R. D. Suenram, *Thermal Decomposition Pathways in Nitramine Propellants. Final Rep., USARO Contract 29596-CH, Gaithersburg*, MD, NIST (1995).

[245] G. W. Lemire, J. B. Simeonsson, and R. C. Sausa, Anal. Chem. **65**, 529 (1993).

[246] M. W. Todd *et al.*, Appl. Phys. B: Lasers Opt. **75**, 367 (2002).

[247] A. D. Usachev, T. S. Miller, J. P. Singh, F. Y. Yueh, P. R. Jang, and D. L. Monts, Appl. Spectrosc. **55**, 125 (2001).

[248] S. F. Fulghum, *Detection of Explosives Vapor at the PPT Level with a Laser Interferometric Calorimeter, Rep. SRL-05-F-1993, Sci. Res. Lab.*, Inc., Somerville, MA (1993).

[249] S. D. Fulghum and M. M. Tilleman, J. Opt. Soc. Am. B **8**, 2401 (1991).

[250] L. G. Rosengren, Appl. Opt. **14**, 1960 (1975).

[251] P. C. Claspy, in *Optoacoustic Spectroscopy and Detection*, edited by Y.–H. Pao (Academic, New York, 1977), pp. 133–166.

[252] R. A. Crane, Appl. Opt. **17**, 2097 (1978).

[253] B. Schrader and D. S. Moore, Pure Appl. Chem. **69**, 1451 (1997).

[254] B. Schrader, *Infrared and Raman Spectroscopy* (VCH, Weinheim, 1995).

[255] P. Hendra, Ed., Spectrochim. Acta, Part A **46**, 121 (1990).

[256] K. L. McNesby and C. S. Coffey, J. Phys. Chem. B **101**, 3097 (1997).

[257] N. F. Fell, J. M. Widder, S. V. Medlin, J. B. Morris, R. A. Pesce-Rodriguez, and K. L. McNesby, J. Raman Spectrosc. **27**, 97 (1996).

[258] K. L. McNesby, J. E. Wolfe, J. B. Morris, and R. A. Pesce-Rodriguez, J. Raman Spectrosc. **25**, 77 (1994).

[259] F. W. S. Carver and T. F. Sinclair, J. Raman Spectrosc. **14**, 470 (1983).

[260] N. Gupta and R. Dahmani, Spectrochim. Acta, Part A **56**, 1453 (2000).

[261] R. J. Lacey, IEE Conf. Publ. **408**, 138 (1995).

[262] A. Mercado, J. Janni, and B. Gilbert, Proc. SPIE **2511**, 142 (1995).

[263] D. S. Moore, Fresenius' J. Anal. Chem. **369**, 393 (2001).

[264] I. R. Lewis, N. W. Daniel, Jr., N. C. Chaffin, P. R. Griffiths, and M. W. Tungol, Spectrochim. Acta, Part A **51**, 1985 (1995).

[265] C. Cheng, T. E. Kirkbride, D. N. Batchelder, R. J. Lacey, and T. G. Sheldon, J. Forensic Sci. **40**, 31 (1995).

[266] I. P. Hayward, T. E. Kirkbride, D. N. Batchelder, and R. J. Lacey, J. Forensic Sci. **40**, 883 (1995).

[267] K. Kneipp, Y. Wang, R. R. Dasari, M. S. Feld, and B. D. Gilbert, Spectrochim. Acta, Part A **51**, 2171 (1995).

[268] C. Cheng, I. E. Kirkbride, D. N. Batchelder, R. J. Lacey, and T. G. Sheldon, J. Forensic Sci. **40**, 31 (1995).

[269] I. P. Hayward, T. E. Kirkbride, D. N. Batchelder, and R. J. Lacey, J. Forensic Sci. **40**, 883 (1995).

[270] J. Akhavan, Spectrochim. Acta, Part A **47**, 1247 (1991).

[271] M. D. Ray, A. J. Sedlacek, and M. Wu, Rev. Sci. Instrum. **71**, 3485 (2000).

[272] M. Wu, M. D. Ray, K. H. Fung, M. W. Ruckman, D. Harder, and A. J. Sedlacek, Appl. Spectrosc. **54**, 300 (2000).

[273] M. Fleischmann, P. J. Hendra, and A. J. McQuillan, Chem. Phys. Lett. **26**, 163 (1974).

[274] A. Campion, Annu. Rev. Phys. Chem. **36**, 549 (1985).

[275] T. R. Jensen, M. D. Malinsky, C. L. Haynes, and R. P. Van Duyne, J. Phys. Chem. B **104**, 10549 (2000).

[276] P. M. Tessier, O. D. Velev, A. T. Kalambur, J. F. Rabolt, A. M. Lenhof, and E. W. Kaler, J. Am. Chem. Soc. **122**, 9554 (2000).

[277] J. M. Sylvia, J. A. Janni, J. D. Klein, and K. M. Spencer, Anal. Chem. **72**, 5831 (2000).

[278] R. M. Stöckle, V. Deckert, C. Fokas, and R. Zenobi, Appl. Spectrosc. **54**, 1577 (2000).

[279] K. Kneipp, Y. Wang, R. R. Dasari, M. S. Feld, B. D. Gilbert, J. Janni, and J. I. Steinfeld, Spectrochim. Acta, Part A **51**, 2171 (1995).

[280] R. G. Freeman *et al.*, Science **267**, 1629 (1995).

[281] K. C. Grabar, R. G. Freeman, M. B. Hommer, and M. J. Natan, Anal. Chem. **67**, 735 (1995).

[282] C. J. McHugh, R. Keir, D. Graham, and W. E. Smith, Chem. Commun. (Cambridge) **2002**, 580 (2002).

[283] InPhotonics, Inc., a division of EIC Laboratories, Inc., Web URL: www.inphotonics.com Renishaw, Inc., Web URL: www.renishaw.com.

[284] W. R. Seitz and M. P. Neary, Anal. Chem. **46**, 188A (1974).

[285] H. Zuckermann, G. D. Greenblatt, and Y. Haas, J. Phys. Chem. **91**, 5159 (1987).

[286] E. M. Boncyk, in *Third International Symposium on Analysis and Detection of Explosives, Mannheim-Neuostheim*, Germany (1989), pp. 40.41–40.14.

[287] H. O. Funsten and D. J. McComas, US Patent No. 5638166 (1997).

[288] D. D. Wu, J. P. Singh, F. Y. Yeh, and D. L. Monts, Appl. Opt. **35**, 3998 (1996).

[289] A. Mercado, J. Janni, B. Gilbert, and J. I. Steinfeld, in *Proc. Explosives Detection Technology Symp. Aviation Security Technology Conf., 2nd*, Atlantic City, FAA (1996), pp. 91–99.

[290] K. Hasue, S. Nakahara, J. Morimoto, T. Yamagami, Y. Okamoto, and T. Miyakawa, Propellants, Explos., Pyrotech. **20**, 187 (1995).

[291] S. K. VanBergen, I. B. Bakaltcheva, J. S. Lundgren, and L. C. Shriver-Lake, Environ. Sci. Technol. **34**, 704 (2000).

[292] A. Crowson, R. W. Hiley, T. Ingham, T. McCreedy, A. J. Pilgrim, and A. Townshend, Anal. Commun. **34**, 213 (1997).

[293] L. H. Chen, D. McBranch, R. Wang, and D. Whitten, Chem. Phys. Lett. **330**, 27 (2000).

[294] Q. Zhou and T. M. Swager, J. Am. Chem. Soc. **117**, 12593 (1995).

[295] Y. S. Yang and T. M. Swager, J. Am. Chem. Soc. **120**, 5321 (1998).

[296] Y. S. Yang and T. M. Swager, J. Am. Chem. Soc. **120**, 11864 (1998).

[297] M. la Grone, C. Cumming, M. Fisher, M. Fox, S. Jacob, D. Reust, M. Rockley, and E. Towers, Web URL: www.nomadics.com/EM_aerosense_fluor.pdf

[298] C. A. Heller, S. R. Greni, and E. D. Erickson, Anal. Chem. **54**, 286 (1982).

[299] Y. Zhang and W. R. Seitz, Anal. Chim. Acta **221**, 1 (1989).

[300] R. T. Medary, Anal. Chim. Acta **258**, 341 (1992).

[301] T. F. Jenkins and M. E. Walsh, Talanta **39**, 419 (1992).

[302] C. Jian and W. R. Seitz, Anal. Chim. Acta **237**, 265 (1990).

[303] S. Stevanovic and M. Mitrovic, Int. J. Environ. Anal. Chem. **40**, 69 (1990).

[304] Y. Zhang, W. R. Seitz, and C. L. Grant, Anal. Chim. Acta **217**, 217 (1989).

[305] Y. Zhang, W. R. Seitz, D. C. Sundberg, and C. L. Grant, *Preliminary Development of a Fiber Optic Sensor for TNT*, Special Report No. 88-4 (U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, 1988).

[306] D. Arbuthnot, D. U. Bartholomew, R. Carr, J. L. Elkind, L. Gheorghiu, J. L. Melendez, and W. R. Seitz, Proc. SPIE **3392**, 432 (1998).

[307] XPRAY Field Test Kit available from Mistral Group, Web URL: http://www.mistralgroup.com/SEC_explosives.asp

[308] D. L. Eck, M. J. Kurth, and C. Macmillan, in *Immunochemical Methods for Environmental Analysis*, edited by J. M. Van Emon and R. O. Mumma, ACS Symposium Series, Vol. 442 (American Chemical Society, Washington, DC, 1990), pp. 79–94.

[309] S. K. Bhatia, L. C. Shriver-Lake, K. J. Prior, J. H. Georger, J. M. Calvert, R. Bredehorst, and F. S. Ligler, Anal. Biochem. **178**, 408 (1989).

[310] J. M. Van Emon and V. Lopez-Avila, Anal. Chem. **64**, 78A (1992).

[311] C. Keuchel and R. Niessner, Fresenius' J. Anal. Chem. **350**, 538 (1994).

[312] C. Keuchel, L. Weil, and R. Niessner, Anal. Sci. **8**, 9 (1992).

[313] C. Keuchel, L. Weil, and R. Niessner, Fresenius' J. Anal. Chem. **343**, 143 (1992).

[314] L. C. Shriver-Lake, C. H. Patterson, and S. K. Van Bergen, Field Anal. Chem. Tech. **4**, 239 (2000).

[315] S. K. VanBergen, I. B. Bakaltcheva, J. S. Lundgren, and L. C. Shriver-Lake, Environ. Sci. Technol. **34**, 704 (2000).

[316] A. Zeck, M. G. Weller, and R. Niessner, Fresenius' J. Anal. Chem. **364**, 113 (1999).

[317] D. B. Holt, P. R. Gauger, A. W. Kusterbeck, and F. S. Ligler, Biosens. Bioelectron. **17**, 95 (2002).

[318] E. R. Goldman, M. P. Pazirandeh, P. T. Charles, E. D. Balighian, and G. P. Anderson, Anal. Chim. Acta **457**, 13 (2002).

[319] M. Altstein, A. Bronshtein, B. Glattstein, A. Zeichner, T. Tamiri, and J. Almog, Anal. Chem. **73**, 2461 (2001).

[320] J. C. Bart, L. L. Judd, K. E. Hoffman, A. M. Wilkins, and A. W. Kusterbeck, Environ. Sci. Technol. **31**, 1505 (1997).

[321] J. C. Bart, L. L. Judd, K. E. Hoffman, A. M. Wilkins, and A. W. Kusterbeck, Environ. Sci. Technol. **31**, 1505 (1997).

[322] J. C. Bart, L. L. Judd, and A. W. Kusterbeck, Sens. Actuators B **38-39**, 411 (1997).

[323] L. C. Shriver-Lake, B. L. Donner, and F. S. Ligler, Environ. Sci. Technol. **31**, 837 (1997).

[324] U. Narang, P. R. Gauger, and F. S. Ligler, Anal. Chem. **69**, 1961 (1997).

[325] U. Narang, P. R. Gauger, and F. S. Ligler, Anal. Chem. **69**, 2779 (1997).

[326] L. L. Judd, A. W. Kusterbeck, D. W. Conrad, H. Yu, H. L. Myles, Jr, and F. S. Ligler, Proc. SPIE **2388**, 198 (1995).

[327] L. C. Shriver-Lake, K. A. Breslin, J. P. Golden, L. L. Judd, J. Choi, and F. S. Ligler, Proc. SPIE **2367**, 52 (1995).

[328] H. R. Lukens, in *Proc. Int. Symp. Explosive Detection Technology, 1st*, Atlantic City, FAA (1992), pp. 753–758.

[329] J. C. Bart, L. L. Judd, K. E. Hoffman, A. M. Wilkins, P. T. Charles, and A. W. Kusterbeck, in *Development and Applications of Immunoassays for Environmental Analysis*, edited by D. S. Aga and E. M. Thurman, ACS Symposium Series, Vol. 657 (American Chemical Society, Washington, DC, 1996), pp. 210–220.

[330] TNT RaPID Assay Product file, Strategic Diagnostics, Inc., Newark, DE (1995).

[331] L. C. Shriver-Lake, K. A. Breslin, P. T. Charles, D. W. Conard, J. P. Golden, and F. S. Ligler, Anal. Chem. **67**, 2431 (1995).

[332] A. W. Kusterbeck, L. L. Judd, H. Yu, J. Myles, and F. S. Ligler, Proc. SPIE **2092**, 218 (1994).

[333] J. P. Whelan, A. W. Kusterbeck, G. A. Wemhoff, R. Bredehorst, and F. S. Ligler, Anal. Chem. **65**, 3561 (1993).

[334] J. P. Whelan, A. W. Kusterbeck, G. A. Wemhoff, R. Bredehorst, and F. S. Ligler, Anal. Chem. **65**, 3561 (1993).

[335] A. Bromberg and R. A. Mathies, Anal. Chem. **75**, 1188 (2003).

[336] A. J. Bard and L. R. Faulkner, *Electrochemical Methods. Fundamentals and Applications* (Wiley, New York, 1980).

[337] Z. Cao, W. J. Buttner, and J. R. Stetter, Electroanalysis **4**, 253 (1992).

[338] W. J. Buttner, M. Findlay, W. Vickers, W. M. Davis, E. R. Cespedes, S. Cooper, and J. W. Adams, Anal. Chim. Acta **341**, 63 (1997).

[339] J. Wormhoudt, J. H. Shorter, and C. E. Kolb, in *Conference on Field Analytical Methods for Hazardous Wastes and Toxic Chemicals*, Las Vegas, NV (1997).

[340] J. Wormhoudt *et al.*, Appl. Opt. **35**, 3992 (1996).

[341] M. Krausa, J. Doll, K. Schorb, W. Boke, and G. Hambitzer, Propellants, Explos., Pyrotech. **22**, 156 (1997).

[342] J. Wang, B. M. Tian, and E. Sahlin, Anal. Chem. **71**, 5436 (1999).

[343] J. Wang, R. K. Bhada, J. Lu, and D. McDonald, Anal. Chim. Acta **361**, 85 (1998).

[344] J. Wang, F. Lu, D. MacDonald, J. Lu, M. E. S. Ozsoz, and K. R. Rogers, Talanta **46**, 1405 (1998).

[345] J. Wang and M. Pumera, Anal. Chem. **74**, 5919 (2002).

[346] J. Wang, M. Pumera, M. P. Chatrathi, A. Escarpa, and M. Musameh, Anal. Chem. **74**, 1187 (2002).

[347] Q. Lu, G. E. Collins, M. Smith, and J. Wang, Anal. Chim. Acta **469**, 253 (2002).

[348] A. Hilmi and J. H. T. Luong, Environ. Sci. Technol. **34**, 3046 (2000).

[349] J. Yinon, Anal. Chem. **75**, 99A (2003).

[350] K. J. Albert and D. R. Walt, Anal. Chem. **72**, 1947 (2000).

[351] K. J. Albert, M. L. Myrick, S. B. Brown, D. L. James, F. P. Milanovich, and D. R. Walt, Environ. Sci. Technol. **35**, 3193 (2001).

[352] H. Wohltjen and R. Dessy, Anal. Chem. **51**, 1458 (1979).

[353] L. A. Pinnaduwage, in *Third Explosives Detection Technology Symposium & Aviation Security Technology Conference*, Atlantic City, NJ (2001), pp. 602–615.

[354] R. T. Lareau, T. Chamberlain, and S. F. Hallowell, in *Third Explosives Detection Technology Symposium & Aviation Security Technology Conference*, Atlantic City, NJ (2001), pp. 332–339.